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April 22, 1998

DEPARTMENT OF TRANSPORTATION
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DOCKET SECTION

The Honorable Philip R. Recht
Deputy Administrator
NATIONAL HIGHWAY TRAFFIC
SAFETY ADMINISTRATION
400 Seventh Street, S. W., Room 5220
Washington, DC 20590

Dear Mr. Recht:

Re: **Settlement Agreement**
Section F. Computer Modeling

Enclosed is a publication authored by Jian Kang of Engineering Technology Associates, Incorporated and J. T. Wang of General Motors Research and Development Center entitled "ISP - An Airbag Inflator Simulation Program." This report relates to Project F .4 (c) Analysis, Modeling and Integration.

Sincerely,

David A. Collins
Attorney

c: James A. Durkin, Esq.

Enclosure

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GM NON-CLASSIFIED

ISP - An Airbag Inflator Simulation Program

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January 23, 1998

Synopsis or Abbreviated Abstract

An inflator simulation computer program, ISP, has been developed to facilitate the assessment of transient heat transfer models. In addition to providing for incorporation of new transient heat transfer models, this program has several other useful and unique features: 1) it allows gas to have multiple chemical components, 2) it allows gas to use temperature-dependent thermodynamic properties, 3) it can self-generate gas thermodynamic properties through linkage to a chemical kinetic package CHEMKIN, and 4) it allows the users to use either cubic spline or polynomial curve fitting to smooth the noise tank test data. This program can simulate three basic tasks: inflator tank test analysis using either the average temperature method or the dual pressure method, tank test simulation, and bag deployment analysis.

ISP - An Airbag Inflator Simulation Program

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ABSTRACT

An inflator simulation computer program, ISP, has been developed to facilitate the assessment of transient heat transfer models. In addition to providing for incorporation of new transient heat transfer models, this program has several other useful and unique features: 1) it allows gas to have multiple chemical components, 2) it allows gas to use temperature-dependent thermodynamic properties, 3) it can self-generate gas thermodynamic properties through linkage to a chemical kinetic package CHEMKIN, and 4) it allows the users to use either cubic spline or polynomial curve fitting to smooth the noise tank test data. This program can simulate three basic tasks: inflator tank test analysis using either the average temperature method or the dual pressure method, tank test simulation, and bag deployment analysis.

1. INTRODUCTION

The mechanics of transient heat transfer during an airbag inflation process is not fully understood. Industry-wide practice is to assume an adiabatic inflator tank test analysis to generate the required mass flow rate and gas temperature input data for the use of airbag models.

A research program has been initiated at the GM R&D Center with an aim to experimentally quantify the amount of the transient heat transfer, and to develop a computer simulation capability to account for the transient heat transfer of an airbag inflation process. To facilitate the needs of assessing the transient heat transfer models that are being developed, we have developed a math-based tool, called the Inflator Simulation Program or simply ISP. Comparing with other known inflator simulation programs, this FORTRAN program was written with several useful and unique features: 1) it allows gas to have multiple chemical components, 2) it allows gas to use temperature-dependent thermodynamic properties, 3) it can self-generate gas thermodynamic properties through linkage to a chemical kinetic package CHEMKIN, and 4) it allows the users to use either cubic spline or polynomial curve fitting to smooth the noise tank test data. In addition, it provides for incorporation of future transient heat transfer models.

In this paper, we present the theory, computer program structure and usage of ISP with examples.

2 THEORY

Figures 1 and 2 depict the schematic of an inflator tank test and an air-bag inflation process, respectively. There are two types of inflator tank tests, namely the closed tank test (Wang and Nefske, 1988) and the vented tank test (Wang, 1991). The closed tank test is useful for generating the required mass flow rate and gas temperature input data for airbag modeling and analysis, while the vented tank test can be used to discriminate inflators. In what follows, we analyze the more general case – the vented tank test. The results of the vented tank test analysis are equally applicable to the closed tank test case. This is accomplished by simply setting the vent area zero.

We assume that within the test tank and the airbag all thermal properties of the gas or gaseous mixture are well mixed and uniformly distributed (i.e., a lumped parameter approach), and that the gas behaves as an ideal gas or gaseous mixture. We also assume that by the end of the inflation process, all solid propellants are completely consumed.

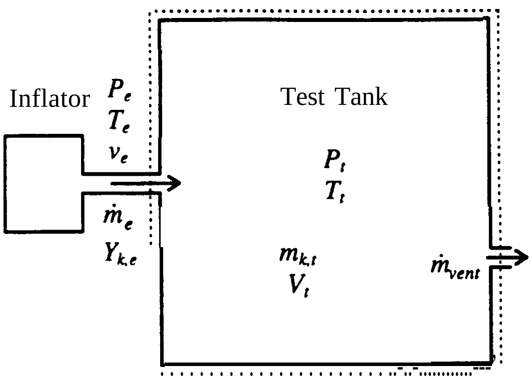

Figure 1 An inflator tank test

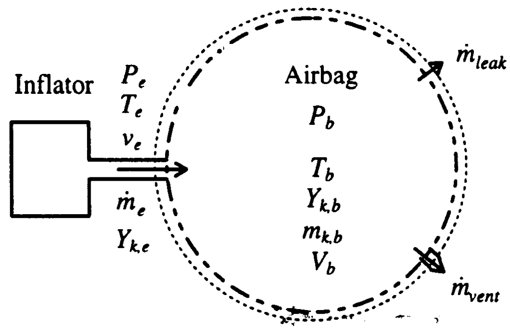

Figure 2 An airbag inflation process

2.1 Inflator Tank Test

The governing equations for an inflator tank test with gas that has multiple chemical components, and that has temperature dependent thermodynamic properties, can be written as

$$\frac{dm_{k,t}}{dt} = Y_{k,e}\dot m_e - Y_{k,t}\dot m_{vent} \tag{1}$$

$$m_t c_{v,t}\frac{dT_t}{dt} = m_e\left(h_e - \sum e_{k,t}Y_{k,e}\right) - m_{vent}\frac{R_u}{\overline{W}_t}T_t - Q \tag{2}$$

$$P_t V_t = \sum \frac{m_{k,t}}{W_k} R_u T_t \tag{3}$$

$$\dot P_t V_t = \sum \frac{\dot m_{k,t}}{W_k} R_u T_t + m_t \frac{R_u}{\overline{W}_t}\dot T_t \tag{4}$$

$$\dot m_e = (cA)_e \sqrt{\frac{k_e}{R_e}}\left(\frac{2}{k_e+1}\right)^{\frac{k_e+1}{2(k_e-1)}} \frac{P_e}{\sqrt{T_e}} \qquad if \quad {P_t}/{P_e} \le \left(\frac{2}{k_e+1}\right)^{\frac{k_e}{k_e-1}} \tag{5}$$

$$\dot m_e = (cA)_e \sqrt{\frac{2k_e}{R_e(k_e-1)}\frac{P_e}{\sqrt{T_e}}\left[\left({P_t}/{P_e}\right)^{2/k_e} - \left({P_t}/{P_e}\right)^{{k_e+1}/{k_e}}\right]}^{\,1/2} \tag{6}$$

$$if \quad {P_t}/{P_e} > \left(\frac{2}{k_e+1}\right)^{\frac{k_e}{k_e-1}}$$

$$m_t = \sum m_{k,t} \tag{7}$$

$$h = \sum Y_k h_k \qquad e = \sum Y_k e_k \tag{8}$$

$$c_p = \sum Y_k c_{p,k} \qquad c_v = \sum Y_k c_{v,k} \tag{9}$$

$$c_{v,k} = c_{p,k} - {R_u}/{W_k} \tag{10}$$

$$\frac{1}{\bar{W}} = \sum \frac{Y_k}{W_k} \tag{11}$$

$$h_k = \Delta h^{\circ}_{f,k} + \int_{T_R}^{T} c_{p,k}(T)\, dT \tag{12}$$

$$Y_k = {m_k}/{m}$$

Equation 1 is a species mass conservation equation. Energy conservation is expressed in Eq. 2. Equation of state along with its derivative form are shown in Eqs. 3 and 4, respectively. The inflator nozzle mass flow rates are given in Eqs. 5 and 6. In these equations, P is pressure, T is temperature, Y represents species mass fraction, and Q is the heat loss rate from gas to tank wall. In addition, h is specific enthalpy and e is specific internal energy. $(cA)_e$ is the effective flow area of inflator exit nozzle. Index t refers to tank, k represents a species, and index e designates the inflator exit nozzle. Some constitutive relations are listed in Eqs. 7-13. Please note that here P, T, h and e are stagnation properties, and $c_{p,k}$, the specific heat of species k, is a given function of temperature.

For a two-component system (i.e., the gas from an inflator plus the initial gas in the tank, each with constant thermodynamic properties) the above equations can be reduced to the following forms:

$$\frac{dm_t}{dt} = \dot{m}_e - \dot{m}_{vent} \tag{14}$$

$$m_t c_{v,t} \frac{dT_t}{dt} = \dot{m}_e (c_{p,e} T_e - c_{v,e} T_t) - \dot{m}_{vent} R_t T_t - Q \tag{15}$$

$$P_t V_t = m_t R_t T_t \tag{16}$$

$$\dot{P}_t V_t = \dot{m}_t R_t T_t + m_t \dot{R}_t T_t + m_t R_t \dot{T}_t \tag{17}$$

$$\dot{m}_e = (cA)_e \sqrt{\frac{k_e}{R_e}} \left(\frac{2}{k_e+1}\right)^{\frac{k_e+1}{2(k_e-1)}} \frac{P_e}{\sqrt{T_e}} \qquad if \quad {P_t}/{P_e} \le \left(\frac{2}{k_e+1}\right)^{\frac{k_e}{k_e-1}} \tag{18}$$

$$\dot{m}_e = (CA)_e \sqrt{\frac{2k_e}{R_e(k_e-1)}} \frac{P_e}{\sqrt{T_e}} \left[\left({P_t}/{P_e}\right)^{2/k_e} - \left({P_t}/{P_e}\right)^{k_e+1/k_e} \right]^{1/2} \tag{19}$$

$$if \quad {P_t}/{P_e} > \left(\frac{2}{k_e+1}\right)^{\frac{k_e}{k_e-1}}$$

$$c_{p,t} = k_e c_{v,e} + \frac{m_{t,o}}{m_t}(k_{t,o} c_{v,t,o} - k_e c_{v,e}) \tag{20}$$

$$c_{v,t} = c_{v,e} + \frac{m_{t,o}}{m_t}(c_{v,t,o} - c_{v,e}) \tag{21}$$

$$R_t = c_{p,t} - c_{v,t} \qquad k_t = c_{p,t}/c_{v,t} \tag{22}$$

Two tasks can be formulated using the above equations. The first is a forward tank test simulation, where the gas mass flow rate and temperature time histories of an inflator are given, and the tank pressure P_t, temperature T_t, etc. need to be determined. The above equations can be directly integrated for this purpose. The second is a tank test analysis, in which tank pressure is known, while the inflator exit nozzle mass flow rate $\dot{m}_e$ and temperature T_e are needed. For this kind analysis, we can use either the average temperature method (Wang and Nefske, 1988), if the inflator combustion chamber pressure P_e is not known, or the dual pressure method (Wang, 1989), if P_e is known. The above equations can be rearranged to formulate these two methods. The derived formulations are summarized below.

2.1.1 Average Temperature Method

In this method, the inflator exit nozzle temperature T_e is assumed to be constant. When the test tank pressure time history is given, we can reorganize the above equations to solve for the inflator exit nozzle mass flow rate and temperature, tank temperature, etc.:

$$\dot{m}_e = \left(\dot{P}_t V_t c_{v,t} \overline{W}_t / R_u + Q\right) / \left(T_t c_{v,t} \overline{W}_t / \overline{W}_e + h_e - \sum Y_{k,e} e_{k,t}\right) \tag{23}$$

$$\frac{dm_{k,t}}{dt} = Y_{k,e}\dot{m}_e - Y_{k,t}\dot{m}_{vent} \tag{24}$$

$$T_t = P_t V_t \Big/ \sum \frac{m_{k,t}}{W_k} R_u \tag{25}$$

$$m_t = \sum m_{k,t} \tag{26}$$

$$h = \sum Y_k h_k \qquad e = \sum Y_k e_k \tag{27}$$

$$c_p = \sum Y_k c_{p,k} \qquad c_v = \sum Y_k c_{v,k} \tag{28}$$

$$c_{v,k} = c_{p,k} - R_u / W_k \tag{29}$$

$$\frac{1}{\overline{W}} = \sum \frac{Y_k}{W_k} \tag{30}$$

$$h_k = \Delta h^\circ_{f,k} + \int_{T_R}^{T} c_{p,k}(T)\, dT \tag{31}$$

$$Y_k = m_k / m \tag{32}$$

This set of equations can also be reduced to a simplified form for a two-component system each with constant properties:

$$\dot{m}_e = \frac{c_{v,t}\dot{P}_t V_t + R_t Q}{(c_{v,t}R_e - c_{v,e}R_t)T_t + c_{p,e}R_t T_e} \tag{33}$$

$$T_t = {P_t V_t}\big/{m_t R_t} \tag{34}$$

$$c_{p,t} = k_e c_{v,e} + \frac{m_{t,o}}{m_t}(k_{t,o}c_{v,t,o} - k_e c_{v,e}) \tag{35}$$

$$c_{v,t} = c_{v,e} + \frac{m_{t,o}}{m_t}(c_{v,t,o} - c_{v,e}) \tag{36}$$

$$R_t = c_{p,t} - c_{v,t} \qquad\qquad k_t = {c_{p,t}}\big/{c_{v,t}} \tag{37}$$

In the solution process, an iteration has to be utilized to get the correct average temperature T_e. This procedure is highlighted below with m_{prop} designating the total mass of solid propellant gas products:

<u>Step 1</u> Guess an initial value for T_e,

$$T_e = \frac{V_t(P_{t,final} - P_{t,o})}{k_e R_e m_{prop}}$$

<u>Step 2</u> Integrate the governing equations and find the net gas mass discharged into the tank,

$$\Delta m_t = m_{t,final} - m_{t,o}$$

<u>Step</u> if $\left|\Delta m_t / m_{prop} - 1\right| > \varepsilon$, where ε is a small number for error control, update the average temperature T_e by,

$$T_{e,new} = \frac{1}{2}(1 + \frac{\Delta m_t}{m_{prop}})T_e$$

and return to Step 2. Otherwise, the accuracy has been reached and stop the iteration.

2.1.2 Dual Pressure Method

When the inflator combustion chamber pressure history is measured along with that of test tank pressure, the dual pressure method (Wang, 1989) can be used to evaluate the inflator output parameters $\dot{m}_e$ and T_e, in which the assumption that T_e is constant is removed. For this method, we can rearrange the fundamental governing equations (Eqs. 1-13) into the following forms:

$$c_{e2}(cA)_e P_e(h_e - \sum Y_{k,e}e_{k,t}) - (\frac{\dot{P}_t V_t c_{v,t}\overline{W}_t}{R_u} + Q)\sqrt{T_e} + c_{e2}(cA)_e P_e \frac{c_{v,t}\overline{W}T_t}{\overline{W}_e} = 0 \tag{38}$$

$$\dot{m}_e = (cA)_e c_{e2}\frac{P_e}{\sqrt{T_e}} \tag{39}$$

$$\frac{dm_{k,t}}{dt} = Y_{k,e}\dot{m}_e - Y_{k,t}\,\dot{m}_{vent} \tag{40}$$

$$T_t = {P_t V_t} \Big/ \sum \frac{m_{k,t}}{W_k} R_u \tag{41}$$

$$m_t = \sum m_{k,t} \tag{42}$$

$$c_{e2} = \sqrt{\frac{k_e}{R_e}} \left(\frac{2}{k_e + 1} \right)^{\frac{k_e+1}{2(k_e-1)}} \qquad if \qquad {P_t}/{P_e} \le \left(\frac{2}{k_e+1} \right)^{\frac{k_e}{k_e-1}} \tag{43}$$

$$c_{e2} = \sqrt{\frac{2k_e}{R_e(k_e-1)}} \left((\frac{P_t}{P_e})^{\frac{2}{k_e}} - (\frac{P_t}{P_e})^{\frac{k_e+1}{k_e}} \right)^{\frac{1}{2}} \qquad if \qquad {P_t}/{P_e} \ge \left(\frac{2}{k_e+1} \right)^{\frac{k_e}{k_e-1}} \tag{44}$$

$$h = \sum Y_k h_k \qquad e = \sum Y_k e_k \tag{45}$$

$$c_p = \sum Y_k c_{p,k} \qquad c_v = \sum Y_k c_{v,k} \tag{46}$$

$$c_{v,k} = c_{p,k} - {R_u}/{W_k} \tag{47}$$

$$\frac{1}{W} = \sum \frac{Y_k}{W_k} \tag{48}$$

$$h_k = \Delta h^\circ_{f,k} + \int_{T_R}^{T} c_{p,k}(T)\,dT \tag{49}$$

$$Y_k = {m_k}/{m} \tag{50}$$

For a two-component system each with constant properties, above equations are reduced to:

$$c_{e2}(cA)_e P_e R_t c_{p,e} T_e - (\dot{P}_t V_t c_{v,t} + R_t Q)\sqrt{T_e} + c_{e2}(cA)_e P_e T_t c_{v,t} c_{v,e}(k_e - k_t) = 0 \tag{51}$$

$$\dot{m}_e = (cA)_e c_{e2} \frac{P_e}{\sqrt{T_e}} \tag{52}$$

$$T_t = {P_t V_t}/{m_t R_t} \tag{53}$$

$$c_{e2} = \sqrt{\frac{k_e}{R_e}} \left(\frac{2}{k_e + 1} \right)^{\frac{k_e+1}{2(k_e-1)}} \qquad if \qquad {P_t}/{P_e} \le \left(\frac{2}{k_e+1} \right)^{\frac{k_e}{k_e-1}} \tag{54}$$

$$c_{e2} = \sqrt{\frac{2k_e}{R_e(k_e-1)}\left((\frac{P_t}{P_e})^{\frac{2}{k_e}} - (\frac{P_t}{P_e})^{\frac{k_e+1}{k_e}}\right)}^{\frac{1}{2}} \qquad if \quad P_t/P_e \geq \left(\frac{2}{k_e+1}\right)^{\frac{k_e}{k_e-1}} \tag{55}$$

$$c_{p,t} = k_e c_{v,e} + \frac{m_{t,o}}{m_t}(k_{t,o}c_{v,t,o} - k_e c_{v,e}) \tag{56}$$

$$c_{v,t} = c_{v,e} + \frac{m_{t,o}}{m_t}(c_{v,t,o} - c_{v,e}) \tag{57}$$

$$R_t = c_{p,t} - c_{v,t} \qquad k_t = c_{p,t}/c_{v,t} \tag{58}$$

Eq. 38 or Eq. 5 1 is used to solve for the inflator exit temperature T_e. Because of temperature-dependent properties and multiple components, they are nonlinear equations, and thus have to be solved by iteration at each time step. On the other hand, an iterative procedure has to be adopted in order to evaluate the effective inflator exit nozzle flow area $(CA)_e$. This procedure is similar to that in average temperature method and is listed below:

Step 1 Assume an initial value of effective flow area $(CA)_e$.

Step 2 Integrate the governing equations and find the net gas mass discharged into the tank,

$$\Delta m_t = m_{t,final} - m_{t,o}$$

Step 3 If $\left|\Delta m_t / m_{prop} - 1\right| > E$, where E is a small number for error control, update the effective flow area $(cA)_e$ by,

$$(cA)_{e\,new} = \frac{1}{2}(1 + \frac{m_{prop}}{\Delta m_t})(cA)_e$$

and return to Step 2. Otherwise, the accuracy has been reached and stop the iteration.

2.2 Airbag Inflation Process

For the airbag inflation process, the governing equations can be summarized as below (Wang, 1988):

$$P_b = P_o \qquad if \; V_b \leq V_{bo}$$

$$P_b = P_o + \frac{1}{c_s}\left(V_b/V_{bo} - 1\right) \qquad if \; V_b \geq V_{bo} \tag{59}$$

$$\frac{dm_{k,b}}{dt} = Y_{k,e}\dot{m}_e - Y_{k,b}\dot{m}_{vent} - Y_{k,b}\dot{m}_{leak} \tag{60}$$

$$m_b c_{v,b}\frac{dT_b}{dt} = \dot{m}_e(h_e - \sum e_{k,b}Y_{k,e}) - (\dot{m}_{vent} - \dot{m}_{leak})\frac{R_u}{\overline{W_k}}T_b - P_b\dot{V}_b - Q \tag{61}$$

$$P_b V_b = \sum \frac{m_{k,b}}{W_k} R_u T_b \tag{62}$$

$$\dot{V}_b = \frac{1}{P_b}\left(\sum \frac{\dot{m}_{k,b}}{W_k} R_u T_b + m_b \frac{R_u}{\overline{\overline{W}}_b}\dot{T}_b\right) \qquad if \quad V_b \le V_{bo}$$

$$\dot{V}_b = \frac{1}{P_b}\left(\sum \frac{\dot{m}_{k,b}}{W_k} R_u T_b + m_b \frac{R_u}{\overline{\overline{W}}_b}\dot{T}_b - \dot{P}_b V_b\right) \qquad if \quad V_b > V_{bo} \tag{63}$$

$$\dot{m}_{\substack{vent\\leak}} = (cA)_{\substack{vent\\leak}} \sqrt{\frac{k_b}{R_b}\left(\frac{2}{k_b+1}\right)^{\frac{k_b+1}{2(k_b-1)}}} \frac{P_b}{\sqrt{T_b}} \qquad if \quad {}^{P_o}\!/_{P_b} \le \left(\frac{2}{k_b+1}\right)^{\frac{k_b}{k_b-1}} \tag{64}$$

$$\dot{m}_{\substack{vent\\leak}} = (cA)_{\substack{vent\\leak}} \sqrt{\frac{2k_b}{R_b(k_b-1)}} \frac{P_b}{\sqrt{T_b}} \left[\left({}^{P_o}\!/_{P_b}\right)^{2/k_b} - \left({}^{P_o}\!/_{P_b}\right)^{k_b+1/k_b}\right]^{1/2} \tag{65}$$

$$if \quad {}^{P_o}\!/_{P_b} > \left(\frac{2}{k_b+1}\right)^{\frac{k_b}{k_b-1}}$$

$$m_b = \sum m_{k,b} \tag{66}$$

where, c_s is the bag fabric stretch factor and V_{bo} is the bag taut-volume. Subscript b refers to bag, subscripts vent and *leak* designate bag vent and leaking, respectively, and subscript o means ambient condition. This set of equations can also be reduced to a simplified form for a two-component system each with constant properties.

For the airbag inflation process, the inflator exit nozzle mass flow rate and temperature are usually provided, and we can rearrange the above equations and integrate them to get time histories of bag pressure P_b, temperature T_b, bag volume V_b, etc.

3. PROGRAM STRUCTURE AND USAGE

A FORTRAN program, ISP, has been developed to solve the above governing equations, together with the proper initial conditions. The computer program incorporates a chemical kinetic package CHEMKIN (Kee, etc. 1980) to evaluate the thermodynamic properties for all species if it is a multi-component, temperature dependent problem, and employs an ordinary differential equation solver LSODE to solve the governing equations. In addition, all chemical species are characterized in terms of standard-state, temperature-dependent specific heat functions, standard enthalpies of formation and standard entropies of formation. These chemical species data are taken directly form a standard JANNAF source (Chase, etc. 1985).

3.1 Program Structure And Input File Format

The ISP package consists of two executable files and several I/O files. The structure of the program is shown in Fig. 3.

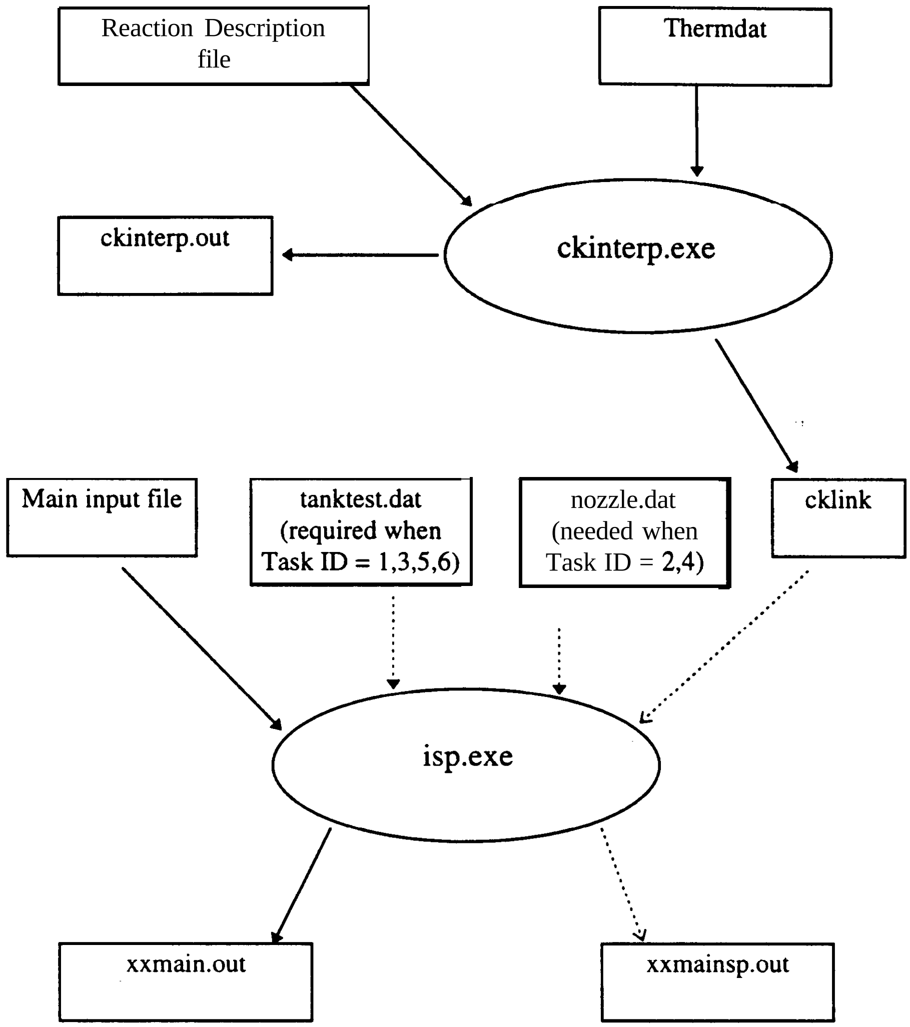

Figure 3 ISP program structure

3.1.1 CHEMKIN Interpreter

The first part of the package is called CHEMIUN interpreter (Kee, etc. 1980). This part pre-processes the chemical system and is required only if variable thermal properties are desired. When we run ***ckinterp.exe***, it reads chemical system information from the file ***Reaction Description,*** draws thermal property data from the file ***thermdat***, and creates a binary link file ***cklink*** which will be read by ***isp.exe***. An ASCII output file ***ckinterp.out*** is also created to document any error messages. The files involved are summarized as follows:

(a.) ***Reaction Description***

This is a user supplied ASCII file that describes the involved chemical system. An example of this file is shown below.

ELEMENTS
0 N AR

```
END
SPECIES
 02 N2 AR
END
```

In this example, three chemical species (O_2, N_2 and Ar) involving three chemical elements (0, N and Ar) are described. Note that all chemical species involved in calculation must be declared.

(b.) ***thermdat***

An ASCII data file containing thermodynamic data for over 700 species. This file is included in the ISP package.

(c.) ckinterp.exe

An executable file which reads the file ***Reaction Description*** and file ***thermdat***, and writes the results to files ***cklink*** (binary) and ***ckinterp.out***.

(d.) ***cklink***

A binary link file generated by executing ***ckinterp.exe***, which contains thermal property data and will be read by ***isp.exe***.

(e.) ckinterp.out

An ASCII output file created by running ***ckinterp.exe***. The user should check this file to make sure everything is correctly interpreted.

3.1.2 *isp.exe*

This is the core element of the inflator simulation program. When ***isp.exe*** is executed, it reads the ***files main input file***, ***tanktest.dat*** or ***nozzle.dat***, and ***cklink*** (if it is a variable thermal property problem). The output from running ***isp.exe*** is written into the file ***xxmain.out***, where ***xx*** is a user provided prefix for the output file name. If there is a problem with variable thermal properties, a file ***xxsp.out*** is also created. These files are detailed in the following.

(a.) ***main input file***

This is a user provided ASCII input file which contains the specifications for the simulation, such as task id, integration time control, thermal property data, and various hardware parameters and initial conditions. It consists of several data groups. A sample file is given below, along with corresponding explanations.

```
JOB TITLE                   !head of job title data group
This is a demo case         !job title, no more than 60 characters
TASK                        !head of task data group
6                           !task id TID, one of 1 - 6,
                            !1 = inflator tank test analysis
                            !2 = inflator tank test simulation
                            !3 = inflator tank test analysis,
                            !    followed by inflator tank test simulation
                            !4 = airbag deployment simulation
                            !5 = inflator tank test analysis,
                            !    followed by airbag deployment simulation
                            !6 = inflator tank test analysis,
                            !    followed by inflator tank test simulation
                            !    and airbag deployment simulation
TIME CONTROL                !head of integration time control data group
0.08, 0.001                 !total integration time (s), time step size dt (s)
```

```
THERMAL PROPERTIES             !head of thermal properties data group
constant                       !one of 'constant' or 'variable'
inflator exit 1.29, 1023.4     !for 'constant', inflator exit nozzle k, Cv (J/(kg-K))
tank/bag initial 1.4, 717.5    !for 'constant', tank and/or bag initial k, Cv (J/(kg-K))
!variable
TANK OR BAG IC                 !head of tank and/or bag initial conditions data group
98.597, 2 1.4                  !tank and/or bag initial pressure (KPa-abs) & temperature (C)
TANK VOLUME & VENT AREA !head of tank volume and vent area data group. Required if TID != 4
0.1, 0.0                       !tank volume (m^3), effective tank vent area cA, (m^2)
ANALYSIS METHOD                !head of tank test analysis method data group.
                               ! Required if TID = 1,3,5,6
! tave                         !one of 'TAVE','PP
pp
RAW DATA PROCESSING            !head of raw data processing data group. Required if TID = 1,3,5,6
cubic spline                   !one of 'cubic spline' or 'curve fitting'
!curve fitting 5               !for 'curve fitting', the followed number is the max. degree allowed
PROPELLANT DATA                !head of inflator propellant data group. Required if TID = 1,3,5,6
0.368, 0.428                   !charger mass (kg), gas product percentage
BAG DATA                       !head of bag data group. Required if TID = 4,5,6
0.05, 0.001E-3                 !bag taut-volume Vb0 (m^3), fabric stretch factor Cs (l/Pa)
BAG V. & L. AREAS              !head of effective bag vent and leaking area data group.
                               ! Required if TID = 4,5,6
6.45E-4, 0.0                   !effective bag vent area cAv, (m^2), and leaking area cAl, (m^2)
!following data required only for variable thermal properties
INITIAL TANK/BAG GAS COMPOSITION !head of initial tank and/or bag gas composition data group
02 1.0                         !species symbol, mole number (in proportion)
N2 3.76
END                            !needed here to indicate the end of species input
NOZZLE GAS COMPOSITION         !head of nozzle gas composition data group
AR 1.0                         !species symbol, mole number (in proportion)
N2 1.0
END                            !needed here to indicate the end of species input
```

Note:

i. The appearing sequence of all data groups must be followed exactly. For a particular task id, some data groups may not be necessary. If these data groups are provided, the program will issue a warning message, skip these data, and continue.

ii. It is not case sensitive, and all numerical data are format free.

iii. Task id TID should be one of 1 - 6. The meaning of TID is explained below:

- TID = 1 This is an inflator tank test analysis. Tank pressure history and/or combustion pressure history are read in from file tanktest.dat. Inflator nozzle mass flow rate and temperature are obtained by using either average temperature method or dual pressure method.
- TID = 2 A tank test simulation process. Inflator output (nozzle mass flow rate and temperature) are read in from file nozzle.dat and the tank pressure, temperature, etc. are the main output for this simulation.
- TID = 3 This is essentially task 1, followed by task 2. But instead of obtaining inflator output from file nozzle.dat, the inflator output resulted from running task 1 serves as the input for running task 2.
- TID = 4 This is an airbag deployment simulation. Inflator output (nozzle mass flow rate and temperature) is read in from file nozzle.dat. Bag time histories of pressure, temperature, volume, etc. are obtained.
- TID = 5 Similarly, this is a combination of task 1 and task 4. The inflator nozzle mass flow rate and temperature required for running task 4 are acquired internally from the results of task 1.
- TID = 6 A complete combination of task 1, task 2, and task 4. After running task 1, the

resulted inflator nozzle mass flow rate and temperature are fed to task 2 and task 4 as input for tank test simulation and bag deployment simulation, respectively.

iv. Tank vent area under 'TANK VOLUME & VENT AREA' is used only for tank test simulation when TID = 2,3,6

v. When 'curve fitting' (under 'RAW DATA PROCESSING' data group) is specified, only tank pressure and tank temperature (if applicable) are treated with polynomial curve fitting technique, since their derivatives are required. All other raw data are still smoothed with cubic spline method. The numerical number after 'curve fitting' is the maximum degree allowed for polynomial curve fitting. The actual degree used in the fitting is controlled automatically to satisfy RMS of relative fitting error (set to 0.01 in code). Currently, the upper limit for this number is set to 10.

vi. The initial pressure under 'TANK OR BAG IC' data group is also served as the atmospheric reference pressure.

vii. 'INITIAL TANK GAS COMPOSITION' and 'NOZZLE GAS COMPOSITION' data groups are required only if 'variable' thermal property option is selected. The numerical values after each species symbol are the mole numbers in proportion. It is not necessary for them to be mole fractions.

viii. In this file, blank lines and leading blank spaces are allowed, and anything after exclamation mark '!' is treated as a comment.

(b.) ***tanktest.dat***

This is a user provided ASCII file with tank test results. It is required only when task id TID = 1,3,5,6. It has three columns. The first column is for time in seconds, the second column is for tank gage pressure in kPa, and the third, not required for the average temperature method, is for inflator gage pressure in psi. All data in this file are format free. A sample for this file is shown below

0	*0*	3.32693
0.002	0	1.87658
0.004	0	39.5857
0.006	0	139.75
0.008	2.197	770.834
0.010	5.040	1239.48
.	.	.
.		
0.076	430.6	100.6
0.078	43 1.9	84.5
0.080	432.3	77.3

(c.) nozzle.dat

This is a user provided ASCII file with inflator exit nozzle output, and is needed only when task id TID = 2,4. It has three columns. The first column is for time in seconds, the second column is for nozzle mass flow rate in kg/s, and the third is for nozzle stagnation temperature in degrees Kelvin. All data in this file are format free. A sample for this file is shown below

.000	.000	294.55
.001	.000	294.55
.002	.080	152.61
.003	.253	83.919
.004	.ooo	83.919
.005	.ooo	83.919
.	.	.
.	.	
.078	.262	528.92
.079	.484	138.69
.080	.000	77.990

(d.) ***cklink***

This file is needed only if the ‘variable’ thermal properties option is chosen in the main input file. It is a binary file created by running *ckinterp.exe* and is read by *isp.exe*.

(e.) isp. exe

An executable file which carries out the inflator simulation.

(f.)***xxmain.out***

This is the main output file with analysis control parameters and time histories of various variables. *xx* is a user provided prefix. A sample of *xxmain.out* is provided below.

```
|--------------------------------------------------------------------------------|
                                                                                  |
|            **************************************                               |
|             * INFLATOR SIMULATION PROGRAM *                                     |
|            **************************************
|                          (Version 5/23/97)



| Job Title
| --------------------
|     This is a demo case                                                         |
|
I Task
| --------------------
|     task ID              = 6
|
I Time Control
| -em-----------------                                                            |
|     total time           = .080 s                                               |
|     time step size       = .001 s                                               |
                                                                                  |
| Thermal Properties                                                              |
| --------------------
|     constant properties
|       inflator exit nozzle
|         gamma            = 1.290
|         cv               = 1023.4 J/kg-K                                        |
|       tank/bag initial gas                                                      |
|         gamma            = 1.400
|         cv               = 717.5 J/kg-K
|
I Tank or Bag IC
| ----------m-m-------                                                            |
|     P-initial            = 98597.0 Pa                                           |
|     T-initial            = 294.5 K                                              |
|                                                                                 |
| Tank Volume & Vent Area
| --------------------
|     tank volume          = .100 m^3
|     eff. vent area       = .000E+00 m^2
```

```
|                                                                      |
| Analysis  Method                                                     |
| --------------------                                                 |
|    PP  -- dual pressure method                                       |
|                                                                      |
| Raw  Data  Processing                                                |
| --------------------                                                 |
|    cubic spline method                                               |
|                                                                      |
| Propellant  Data                                                     |
| -------------------                                                  |
|    propell. mass        = .368 kg                                    |
|    gas fraction         = 42.8 %                                     |
|                                                                      |
| Bag  Data                                                            |
| -------------------                                                  |
|    bag taut-volume      = .0500 m^3                                  |
|    stretch factor       = .10E-05 1/Pa                               |
|                                                                      |
| Bag V. & L. Areas                                                    |
| -------------------                                                  |
|    eff. vent area       = .645E-03 m^2                               |
|    eff. leak area       = .000E+00 m^2                               |
|                                                                      |
|----------------------------------------------------------------------|
```

**** INFLATOR TANK TEST ANALYSIS ****

INFLATOR NOZZLE AND TANK TIME HISTORY

TIME (s)	NOZZLE MASS FLOW RATE (kg/s)	NOZZLE TEMPERATURE (K)	TANK GAS MASS (kg)	TANK GAS TEMPERATURE (K)	HEAT TRANSFER (W)	TANK GAS PRESSURE (KPa-gage)
.000	.000	294.55	.117	294.6	.0E+00	.0
.001	.000	294.55	.117	294.5	.0E+00	.0
.002	.080	152.61	.117	294.5	.0E+00	.0
.					.	
.	.		.		.	.
.078	.262	528.92	.273	663.0	.0E+00	431.9
.079	,484	138.69	.274	662.8	.0E+00	432.2
.080	.000	77.99	.274	661.9	.0E+00	432.3

PRESSURE DERIVATIVE (KPa/s)	INFLATOR PRESSURE (psi-gage)	TANK GAS AVERAGE k	TANKG AVERAGE (J/(kg-K))
.000E+00	3.3	1.400	717.5
-.947E+01	-.7	1.400	717.5
.379E+02	1.9	1.400	717.6
.	.	.	
.532E+03	84.5	1.328	892.9
.167E+03	79.3	1.328	893.0
-.378E-11	77.3	1.328	893.2

**** INFLATOR TANK TEST CURVE GENERATOR ****
INFLATOR TANK TIME HISTORY

TIME (s)	NOZZLE MASS FLOW RATE (kg/s)	NOZZLE TEMPERATURE (K)	TANK GAS MASS (kg)	TANK GAS TEMPERATURE (K)	HEAT TRANSFER (W)	TANK GAS PRESSURE (KPa-gage)
.000	.000	294.55	.117	294.5	.0E+00	.0
.001	.000	294.55	.117	294.6	.0E+00	.0
.002	.080	152.61	.117	294.5	.0E+00	.0
	.	.	.		.	
.	.		.		.	
.078	.262	528.92	.274	658.9	.0E+00	429.5
.079	.484	138.69	.274	658.4	.0E+00	430.0
.080	.000	77.99	.275	657.9	.0E+00	430.0

TANK GAS AVERAGE k	TANK GAS AVERAGE Cv (J/(kg-K))
1.400	717.5
1.400	7 17.5
1.400	717.6
.	.
.	
1.328	893.2
1.328	893.3
1.328	893.5

Total Gas Mass Discharged Into Tank: .1579 kg

**** AIRBAG DEPLOYING ANALYSIS ****
INFLATOR BAG TIME HISTORY

TIME (s)	NOZZLE MASS FLOW RATE (kg/s)	NOZZLE TEMPERATURE (K)	BAG GAS MASS (kg)	BAG GAS TEMPERATURE (K)	TANK GAS PRESSURE (KPa-gage)	BAG VOLUME (m^3)
.000	.000	294.5	.000	294.5	.0	.000000
.001	.000	294.5	.000	294.5	.0	.000000
.002	.080	152.6	.000	190.4	.0	.000014
	.	.	.		.	
.	.		.			.
.078	.262	528.9	.138	774.8	369.4	.067718
.079	.484	138.7	.138	773.0	368.6	.067678
.080	.000	78.0	.138	771.5	367.4	.067619

VENT FLOW OUT RATE (kg/s)	LEAK FLOW OUT RATE (kg/s)	HEAT TRANSFER (W)	BAG FABRIC TEMPERATURE (K)	BAG GAS AVERAGE k	BAG GAS AVERAGE Cv (J/(kg-K))
.0000	.0000	.0E+00	294.5	1.40	717.5

.0000	.0000	.0E+00	294.5	1.39	735.0
.0000	.0000	.0E+00	294.5	1.29	1023.4
.	.	.	.	.	
	.		.	.	.
.	.	.		.	
.4189	.0000	.0E+00	294.5	1.29	1023.4
.4186	.0000	.0E+00	294.5	1.29	1023.4
.4180	.0000	.0E+00	294.5	1.29	1023.4

In this output file, the analysis control parameters, hardware parameters, and initial conditions are echoed first. Depending on task id, the inflator nozzle, tank or airbag time histories resulting from the tank test analysis, tank test simulation, or bag deployment are printed out sequentially.

For tank test analysis, the inflator nozzle and tank time histories are followed. The first column is time. The second and third columns are inflator nozzle mass flow rate and stagnation temperature, respectively. These are the main outputs from this analysis. The calculated tank gas mass, tank gas temperature and heat transfer from gas to tank wall are printed out next. The tank gas pressure and inflator pressure (if applicable), read in as inputs from file tanktest.dat and smoothed in the program, are also written out, along with the tank gas pressure derivative (if applicable). The tank gas mixture specific heat ratio and specific heat at constant volume are also given.

For tank test simulation, the first column is time. The inflator nozzle mass flow rate and stagnation temperature, read from the file *nozzle.dat* or internally acquired from the result of task 1 and smoothed with a cubic spline method in the program, are printed out next. The columns 4, 5, 6 and 7 are for the calculated tank gas mass, temperature, heat transfer from gas to tank wall, and tank gas pressure, respectively. The tank gas mixture specific heat ratio and specific heat at constant volume are also printed out.

For bag deployment analysis, the first three columns are time, echoed inflator nozzle mass flow rate and temperature, respectively. The next four columns are bag mass, temperature, pressure and bag volume, respectively. Mass flow-out rates through bag vent and leaking area are also listed.

(g.) xxsp.out

This file is for tank or bag gas species mass fraction time history. It is generated only if the 'variable' property option is selected in the main input file. A sample file is shown here.

**** INFLATOR TANK TEST ANALYSIS ****
TANK SPECIES MASS FRACTION TIME HISTORY

TIME(s)	02	N2	AR
.000	.233	.767	.000
.001	.233	,767	.000
.002	.233	.766	.001
.	.	.	.
.	.	.	.
.078	.099	.562	.339
.079	.099	.562	.339
.080	.098	.562	.339

**** INFLATOR TANK TEST CURVE GENERATOR ****
TANK SPECIES MASS FRACTION TIME HISTORY

TIME(s)	02	N2	AR
.000	,233	.767	.000

.001	.233	.767	.000
.002	.233	.766	.001
.	.	.	.
.	.	.	.
.078	.099	.562	.339
.079	.099	.562	,339
.080	.098	.562	,339

**** AIRBAG DEPLOYING ANALYSIS ****
BAG SPECIES MASS FRACTION TIME HISTORY

TIME(s)	02	N2	AR
------	-----	-----	-----
.000	.233	.767	.000
.001	.206	.726	.068
.002	.000	.412	.588
.	.	.	.
.	.	.	.
.078	.000	.412	.588
.079	.000	.412	.588
.080	.000	.412	.588

3.2 Execution Procedure

To run the inflator simulation program ISP, the user should first create input files ***Reaction Description*** (if it is a temperature-dependent property problem), ***main input file*** and ***tanktest.dat*** or ***nozzle.dat***, and put all necessary files (including file ***thermdat***) under the same working directory. The user should then follow the procedure listed below. For a constant property problem, skip to Step 2.

Step 1 - Execute CHEMKIN interpreter by issuing

% ckinterp.exe < r-d-f

where r-d-f is the ***Reaction Description*** file name. A binary link file ***cklink*** and ASCII output file ***ckinterp.out*** should be generated. Check the file ***ckinterp.out*** for any error message.

Step 2 - Execute inflator simulation program by issuing

% isp.exe

The user will be prompted to type in a main input file name and a prefix for output files. The program will then read the files ***main input file***, ***tanktest.dat*** or ***nozzle.dat*** and ***cklink*** if applicable, and create the output files ***xxmain.out*** and ***xxsp.out***.

3.3 Limitations

For the current version, the following restrictions are applied in the program:

a. The maximum number of raw data entries for each variable is set to 500.
b. The maximum number of chemical species is set to 50.
c. The highest degree of polynomial curve fitting is 10.

4 EXAMPLES

A test case is carried out to demonstrate the use of the inflator simulation program. In this test case all three basic calculations (inflator tank test analysis, tank test simulation and bag deployment analysis) are requested. Thus, the tank id TID is set to 6. It is assumed that it is a two-component system (inflator exit nozzle stream and tank/bag initial gas) each with constant specific heat ratio and specific heat at constant volume. For the inflator tank test analysis part, the dual pressure method is chosen with tank test data smoothed by a cubic spline method. The bag is assumed to have a vent, but not leaking. The required input files include a ***main input file*** and ***tanktest.dat***, and the output file is ***xxmain.out***. The input and output files are shown in the previous section.

The analysis and simulation results are shown in Figs. 4 - 13. In these figures, solid lines are for inflator tank test analysis, dashed lines represent tank test simulations, and dots refer to bag deployment simulations. From these figures, we can see that the results of an inflator tank test analysis (an inverse process) and tank test simulation (a forward process) are almost identical. This verifies that the program is correct and accurate. It can also be seen on Figs. 12 and 13 that in the bag the specific heat ratio and specific heat jumped to constants of inflator nozzle gas stream immediately after gas flows into gas, since initially the bag has almost zero gas mass.

5 SUMMARY

An inflator simulation computer program, ISP, has been developed to facilitate assessment of transient heat transfer models that are being developed. Comparing with other known inflator simulation programs, this FORTRAN program was written with several useful and unique features: 1) it allows gas to have multiple chemical components, 2) it allows gas to use temperature-dependent thermodynamic properties, 3) it can self-generate gas thermodynamic properties through linkage to a chemical kinetic package CHEMKIN, and 4) it allows the users to use either cubic spline or polynomial curve fitting to smooth the noise tank test data. It also provides for incorporation of future transient heat transfer models. This program can simulate three basic tasks or their combinations: inflator tank test analysis using either the average temperature method or the dual pressure method, tank test simulation, and bag deployment analysis. The results show that the program is reliable and accurate, and could be used as an analysis and design tool for engineers in analyzing and designing inflator/airbag systems.

ACKNOWLEDGMENTS

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NOMENCLATURE

c_v	=	specific heat at constant volume
c_p	=	specific heat at constant pressure
c_s	=	bag fabric stretch factor
(cA)	=	effective flow area
e	=	specific internal energy
h	=	specific enthalpy
A h ;	=	standard enthalpy of formation
k	=	specific heat ratio
m	=	gas mass
$\dot{m}$	=	mass flow rate
m_{prop}	=	total mass of gas products of solid propellants
P	=	pressure
Q	=	rate of heat loss
R	=	gas constant

R_u	=	universal gas constant
t	=	time
T	=	temperature
T_R	=	reference temperature for enthalpy integration
v	=	velocity
V	=	volume
V_{bo}	=	bag taut-volume
W	=	gas molecular weight
$\overline{W}$	=	average gas molecular weight
Y	=	gas species mass fraction

Subscripts

b	=	bag
e	=	inflator exit nozzle
k	=	k^{th} species of gas
$leak$	=	bag leaking
0	=	ambient or initial
t	=	tank
$vent$	=	tank or bag vent

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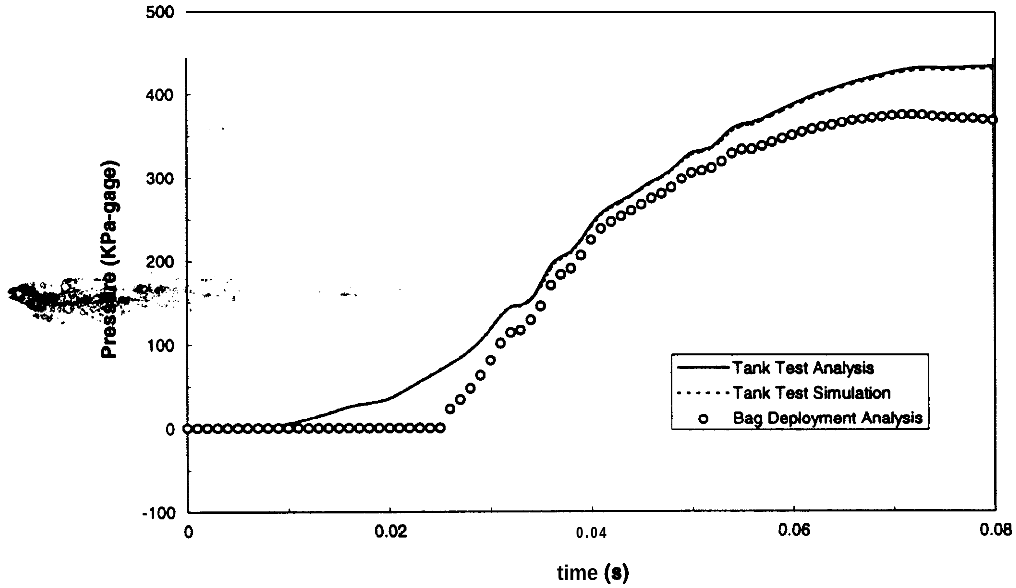

Figure 4 Tank and bag pressure time history

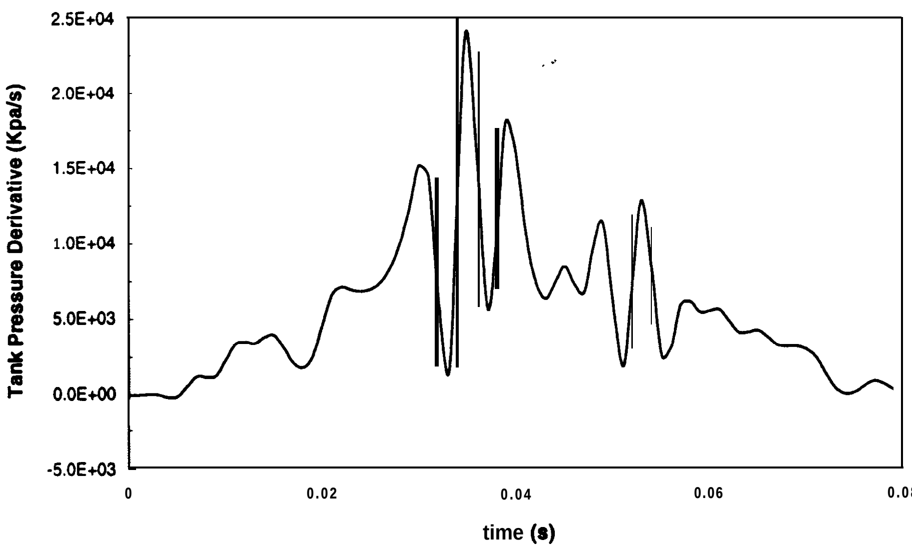

Figure 5 Tank pressure derivative time history

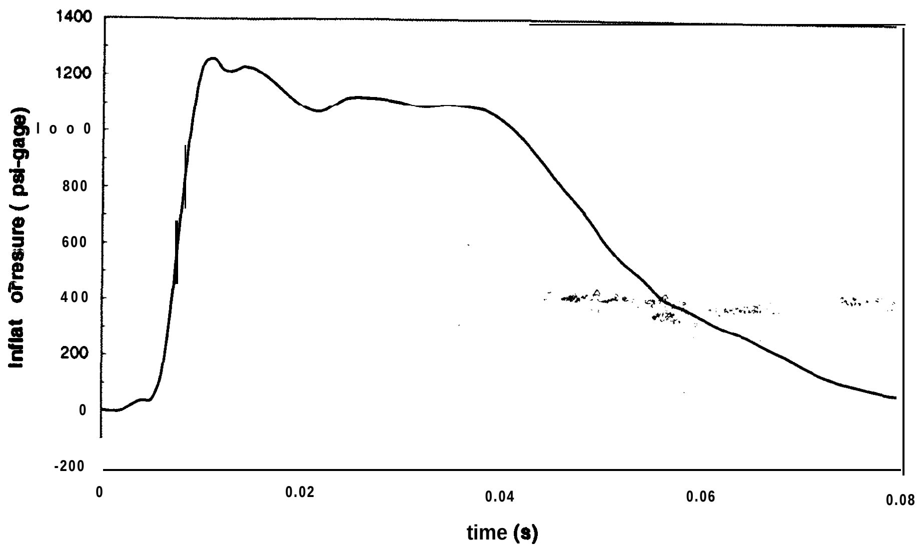

Figure 6 Inflator combustion chamber pressure curve

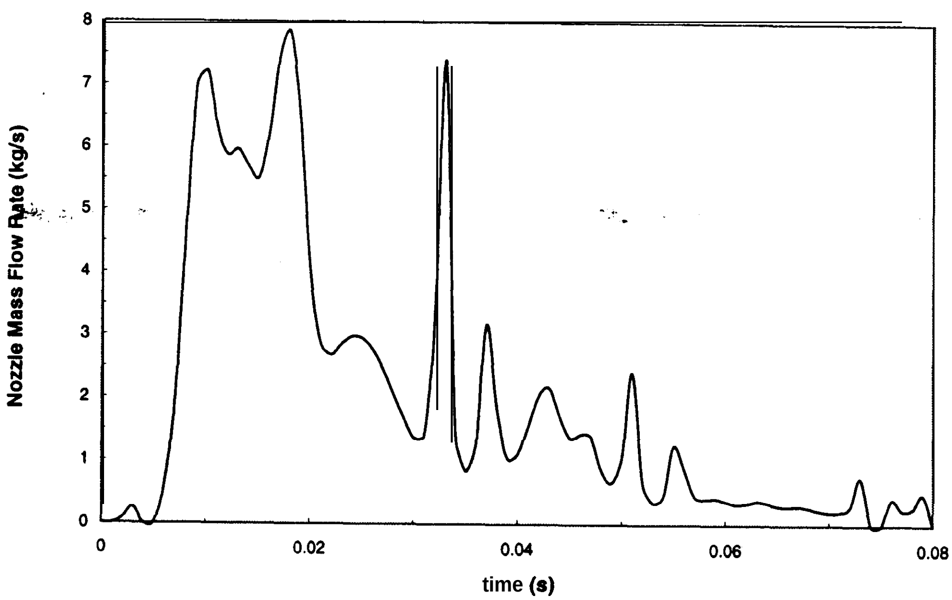

Figure 7 Inflator nozzle mass flow rate time history

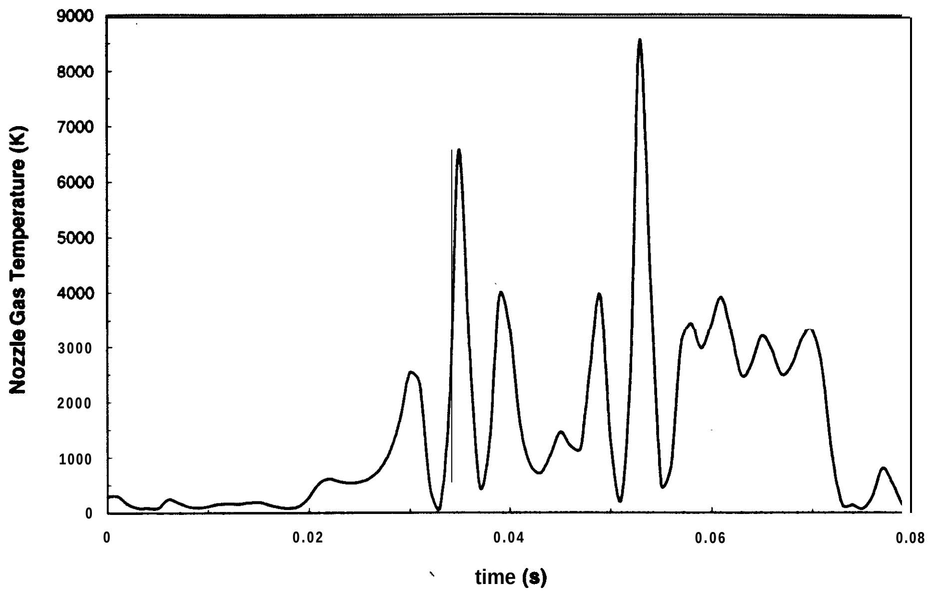

Figure 8 Inflator nozzle gas temperature variation

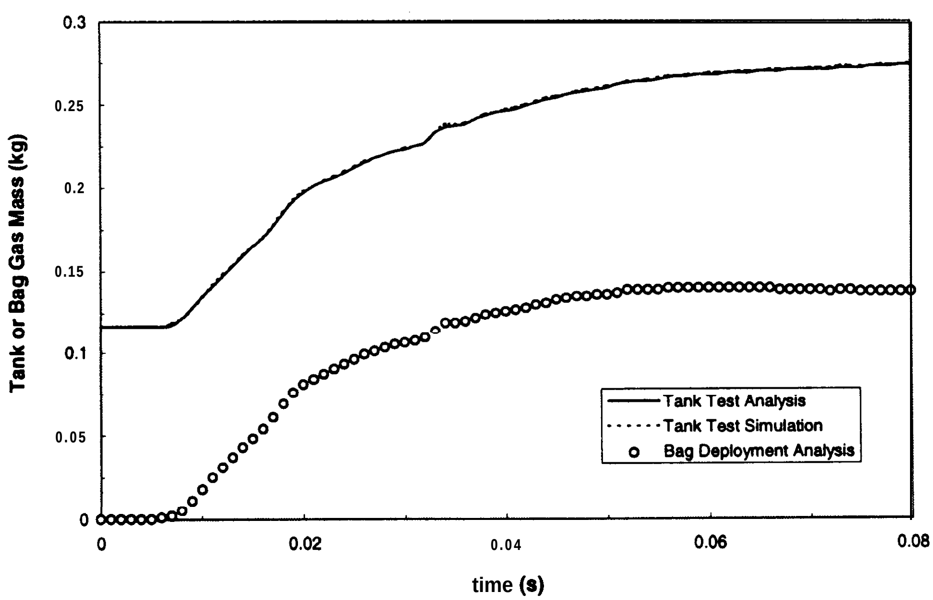

Figure 9 Tank and bag gas masses

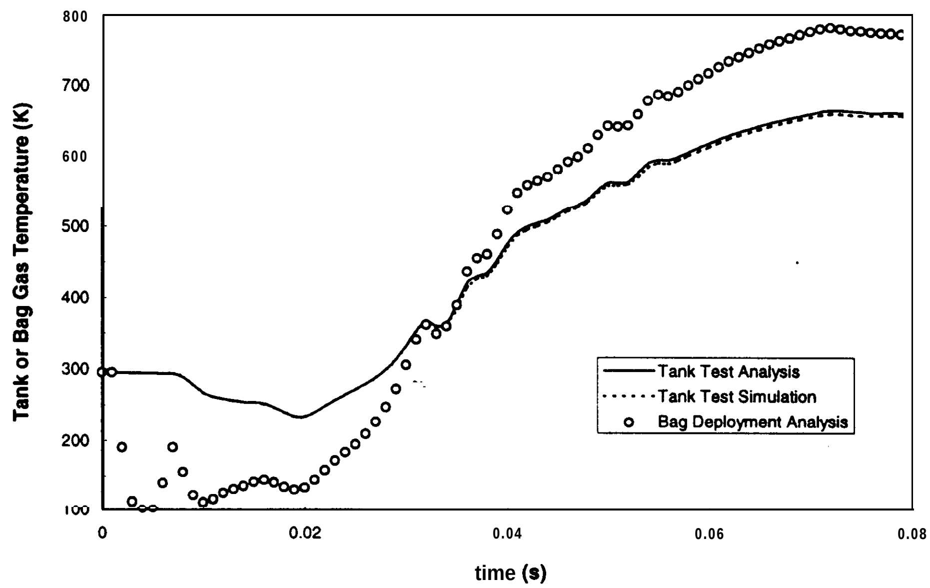

Figure 10 Tank and bag gas temperature

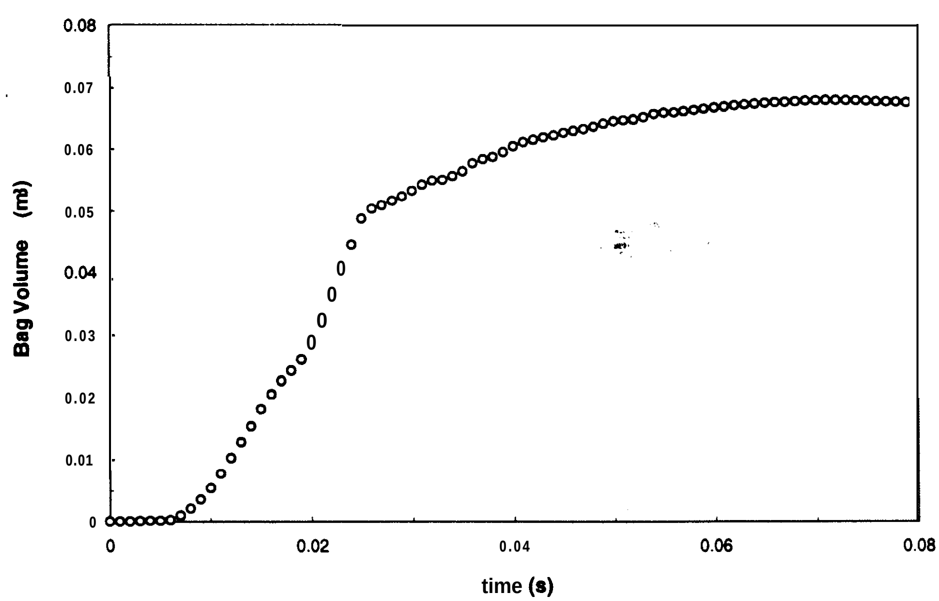

Figure 11 Bag volume time history

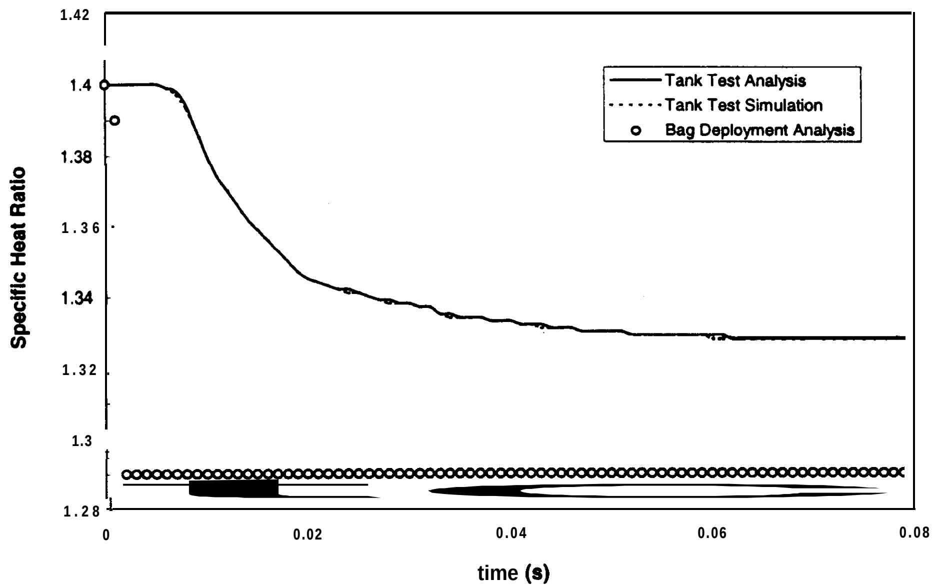

Figure 12 Variation of Tank and bag specific heat ratio

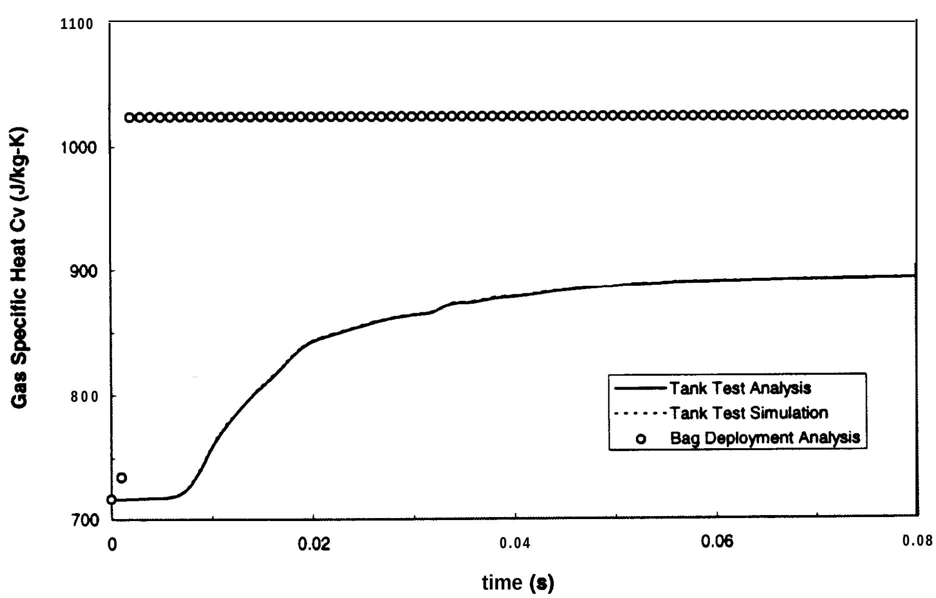

Figure 13 Variation of Tank and bag specific heats at constant volume